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# Nanoscale study on water damage for different warm mix asphalt binders

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## Abstract

In order to analyze the water damage to different warm mix asphalt binders from the micro scale, five kinds of asphalt binders, 70#A base asphalt, sasobit warm mix asphalt, energy champion 120 °C (EC120) warm mix asphalt, aspha-min warm mix asphalt, sulfur-extended asphalt modifier (SEAM) warm mix asphalt, under different conditions (dry/wet, original/aging) are prepared for laboratory tests. The atomic force microscope (AFM) is used to observe the surface properties and measure the adhesion force between the asphalt and the mineral aggregate. The obtained results show that under the dry condition aspha-min warm mix asphalt and SEAM warm mix asphalt show stronger adhesive ability with the mineral aggregate compared with other asphalt binders, but also have relatively large dispersion and fluctuation in the tested results; under the wet condition, aspha-min warm mix asphalt and SEAM warm mix asphalt show stronger water damage resistance ability. The EC120 warm mix asphalt and aspha-min warm mix asphalt are less sensitive to moist, and their corresponding adhesion force is less susceptible to the change of external moisture conditions, leading to a better ability to resist water erosion. The aging process significantly lowers the moisture erosion resistance ability, which further impairs the water damage resistance ability. The base asphalt is more sensitive to moisture and more vulnerable to water damage, no matter whether it is under original or aging conditions. The aging aspha-min warm mix asphalt has the least loss of adhesion force, the smallest dispersion of the tested adhesion force, the strongest water damage resistance ability, no matter it is dry or wet.

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**Keywords:** Road engineering; Warm mix asphalt; Moisture damage; Atomic force microscope; Microcosmic

## 1. Introduction

The material and structural characteristic of asphalt concrete pavement make it more susceptible to the moisture condition. The decrease in the adhesion force causes water damage at the asphalt–aggregate interface. Although the domestic and overseas researches on water damage to asphalt pavement has lasted nearly 70 years, this problem has not yet been effectively addressed. Two key problems

of water damage in asphalt pavement have not been solved thoroughly: How to exactly measure the asphalt mixture performance loss caused by moisture variation? How to effectively reduce the water damage to asphalt pavement?

Numerous studies [1–6] have shown that the water damage of asphalt binders (mixtures) occurs at the molecular scale, or even at the nanometer scale. This is because of the fact that the root cause of water damage to asphalt binders is related to the loss of the adhesion force and the cohesion force. The loss of the adhesion force refers to the decline of the adhesive ability at the asphalt–aggregate interface as a result of the water and water pressure acting on the asphalt mixture; the loss of the cohesion force is due to the softening or the impairment of cohesion capability

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inside the asphalt binder subjected to the moisture and seepage force. Both the adhesion force loss and the cohesion force loss happen at the nanometer scale. Therefore, to quantify the adhesion force or the cohesion force at the nanometer scale is of highly positive practical significance to the research and prevention of water damage to the asphalt pavement.

The microscopic researches on water damage to the asphalt binders at home and abroad mainly focus on base asphalt and SB/SBS modified asphalt. However, there are few reports about the investigation of warm mix asphalt at the nanometer scale. With the application of the high-definition 3D image resolution of the atomic force microscope (AFM) and a precise force–displacement measurement system, the adhesion force between the asphalt–aggregate molecules is analyzed for different asphalt binders under dry/wet, original/aging states at the laboratory, followed by the evaluation of the water damage resistance for each warm mix asphalt binder under different conditions. The research results can provide theoretical basis for the discovery of the mechanism of water damage and the reduction of water damage. It should be noted that parallel tests are conducted in this article using modified asphalt SBS as comparative material, and the results showed no visible difference. In consequence, this article only presented the effects of base asphalt and warm mix modifies on water damage of asphalt binder.

## 2. Review of previous studies

Research on water damage of asphalt binder & mixture dates back to the 1930s, from asphalt to mineral aggregate, from test methodology to pavement structure [7]. To date, numerous test methods have been developed and used to predict moisture-induced damage in asphalt concrete [8–10]. In the past two decades, there have been significant improvements in moisture damage test methods and our understanding of the microscale to macroscale behavior of asphalt concrete. There exists evidence that moisture-induced damage in asphalt concrete is influenced by factors such as asphalt grade, viscosity, modifiers, phenol group concentrations, aggregate surface chemistry, minerals, roughness, porosity, clay coatings, mix air voids, asphalt content, permeability, and binder thickness. Yet, a combination of asphalt and aggregate that would be compatible enough to produce moisture damage-free asphalt concrete is not available [11]. There is an urgent need for the development and assessment of testing methods capable of examining the effect of moisture on asphalt concrete.

Moisture damage within the binder and/or at asphalt–aggregate interfaces has been studied by several researchers [2,6,8]. Recently, the surface free energy of asphalt and aggregate has been empirically related to the moisture-induced damage of asphalt concrete [2,5]. The surface free energy of asphalt and aggregate is indirectly measured using the Wilhelmy plate, sorption device, and Youn–Dupré equation. However, the Wilhelmy plate method can-

not differentiate between the functional groups. For example, the surface free method fails to differentiate between actions of carboxylic acid (bad) and carbonyls (good), or carboxylic acid (bad) and nitrogen compound (good) under wet conditions. Also, the Wilhelmy plate technique cannot clearly distinguish between untreated asphalt and asphalt treated with amine antistrip. By the same token, the universal sorption device requires vacuum degas preconditioning, which is very different from the mixing plant conditions. More recently, Rafiqul et al. [12] tested the adhesion forces between base asphalt as well as SB & SBS modified asphalts and different functional probes. The results showed that modifiers SB and SBS can improve the water damage-proof ability of base asphalt and a 3% SB & SBS dosage can obtain the best effect. In addition, critical parameters for AFM testing on modified asphalt were also confirmed basically.

## 3. Materials and test methods

### 3.1. Raw materials

The raw materials used in the tests include: (1) The base asphalt: 70#A pavement petroleum asphalt. (2) The warm mix modifier sasobit: with low melting point and organic viscosity-reducing character. The admixture dosage is 3.0 percent of the mass of the asphalt binder, which can lower the mixed and compacted temperature by 20 °C–30 °C. (3) The warm mix additive energy champion 120 °C (EC120): a kind of linear aliphatic hydrocarbons. The admixture dosage is 3.0 percent of the mass of the asphalt binder, lowering the mixed and compacted temperature by 20 °C–30 °C. (4) The warm mix additive aspha-min: the artificial synthetic white powder zeolite. The admixture dosage is 0.3 percent of the mass of the asphalt binder, lowering the mixed and compacted temperature by 10 °C–25 °C. (5) The warm mix additive sulfur-extended asphalt modifier (SEAM): the sulfur. The admixture dosage is 30 percent of the mass of the asphalt binder, lowering the mixed and compacted temperature by 20 °C–35 °C. Each appearance of warm mix additives is shown in Fig. 1, and the main technical parameters of the asphalt binders are listed in Table 1.

### 3.2. The preparation of samples

In order to ensure the AFM to reliably observe the nanometer-scale surface properties of asphalt binders, the one-blending method is used to prepare the warm mix asphalt samples which are theoretically finely dispersed and uniformly distributed. In order to make the binder surface smooth, the particle size of asphalt mortar should be as small as possible, an advanced colloid mill machine (2000 mesh) is taken to grind the warm mix asphalt fully mixing the warm agents with the asphalt, at the revolving speed 4500 rpm and grinding time 4 h. The detailed preparation technology is sketched in Fig. 2. Moreover, size of material will not change the character of itself and the



Fig. 1. The appearance of warm mix additives.

Table 1

Main technical indexes of each asphalt binder.

Type of asphalt		Penetration (25 °C) (0.1 mm)	Penetration index <i>PI</i>	Ductility (5 °C) (cm)	Softening point (°C)	Elastic recovery (25 °C) (%)
70#A base asphalt	Original	76	−0.80	19	46.4	–
	After <i>PAV</i> aging	52	−0.68	9.8	52.4	–
Sasobit warm mix asphalt	Original	56	0.37	14.8	63.5	89.1
	After <i>PAV</i> aging	48	0.43	11.0	73.0	82.6
EC120 warm mix asphalt	Original	59	0.46	12.7	61.7	87.4
	After <i>PAV</i> aging	51	0.51	9.8	68.5	81.6
Aspha-min warm mix asphalt	Original	61	0.39	17.9	58.2	89.6
	After <i>PAV</i> aging	53	0.45	12.9	64.3	83.7
SEAM warm mix asphalt	Original	63	0.40	13.5	64.1	91.0
	After <i>PAV</i> aging	54	0.47	8.3	70.4	82.3

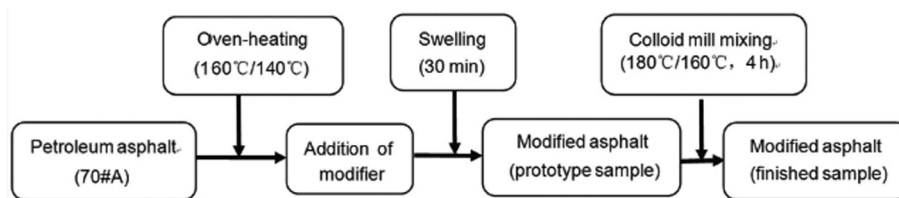


Fig. 2. Preparation process flow chart for warm mix asphalt binder.

usage of colloid mill machine for asphalt binder grinding will also make no difference to the results or the engineering application.

In order to compare the adhesion forces between asphalt and aggregate molecules under different conditions, according to the test code of ASTM D6521, the original

and aging samples are obtained by further processing the residuary asphalts with PAV stress aging (100 °C) which are left after the RTFOT (163 °C) aging. The basic technical parameters for aging asphalt binders are given in Table 1.

In order to prevent further aging, firstly respectively place 20 g of the prepared asphalt binders into an oven at 140 °C and rapidly heat to melt; then drip moderate melted binders on a glass slide and put the glass slide into an oven at 140 °C for five minutes to obtain a smooth surface; finally take out the sample and keep it for natural cooling to room temperature.

For the purpose of comparisons between the dry and wet conditions, making reference to Ref. [12], the wet samples were obtained by firstly putting the dry samples in a vacuum dryer to evacuate to full vacuum and then immersing them in water for 72 h. We obtained totally 20 kinds of original/aging and dry/wet asphalt binders.

Before the AFM tests, all samples were placed into an oven at 140 °C for 2 h for desiccated surfaces.

### 3.3. Method of AFM tests

The Digital Instruments-Veeco Metrology Group AFM with image resolution  $180 \times 180$  points and maximum scanning range  $15 \mu\text{m} \times 15 \mu\text{m}$  is used to perform all tests at the tapping mode. The resonance frequency of micro-cantilever is 260 kHz.

In order to effectively simulate the measurement of asphalt-aggregate adhesion force, the silicon nitride ( $\text{Si}_3\text{N}_4$ ) probe is used to get the three-dimensional images at the asphalt binder surface and measure the adhesion force, under the scanning frequency of 3 Hz, as Silicon is the basic element of rocks and minerals. During experiments, the testing work mainly focused on, the application of the probe, the search of the feature points at the surface of samples, the scan of the image, and the measurement of the force-displacement curves. The scanned figures were further processed using the MATLAB. Ten feature points were scanned for each sample, and the mean value of these ten points was taken as the measured adhesion force.

### 4. The analysis of the AFM images of asphalt binders

The typical micrographs and stereographs for asphalt binders are shown in Fig. 3. Only the figures of the dry samples are provided for the sake of the space. According to the working principle of AFM and the requirement of test accuracy [13–15], the mean value, maximum value and root-mean-square of the surface roughness for each asphalt binder were calculated and are listed in Table 2. As seen in Table 2, the maximum and minimum values of surface roughness RMS are, respectively, 32.46 nm and 7.71 nm. These measured values agree well with the advice for the measurement of surface roughness of viscoelastic material using AFM, which verify the preparation

of the samples and the experimental method adopted in this article.

Besides, both the obtained micrographs and stereographs can visually reflect the degree of surface evenness (or surface roughness) of these samples. Among the five samples, the surface morphology of 70#A base asphalt is relatively smooth, since it has no any additives. Even though there are some slight pits in the 70#A base asphalt, their distributions are relatively uniform. Under the effect of the high-speed shearing of colloid grinder, a uniform and stable spatial network system is generated in the saso-bit warm mix asphalt or the EC120 warm mix asphalt in which several relatively large polymer particles exist, but the two kinds of warm mix additives basically disperse well among the base asphalts, the surface morphology of the binders being relatively smooth and even, which constitutes a good compatible system. The surfaces of aspha-min warm mix asphalt and SEAM warm mix asphalt are very rough with many sags and crests under irregular distributions. The maximum height in Z-axis is about 50 nm. This indicates that the addition of warm mix additives aspha-min and SEAM into the base asphalt significantly increases the granular size and dispersion degree of the mixed particles, thus the compatibility is poorer than that of other warm mix binders [16].

### 5. The measurement of adhesion force

The force-distance curves of the dry original samples for all warm mix asphalts are shown in Fig. 4. The horizontal axis in Fig. 4 represents the distance between the  $\text{Si}_3\text{N}_4$  probe and the sample surface, and the vertical axis represents the magnitude of the force between the probe molecule and the asphalt molecule, positive values for repulsive forces and negative values for attractive forces. Each test cycle starts at the position with a distance bigger than 500 nm from the sample surface. The curves in Fig. 4 show that there are four representative sections, respectively separated by points A, B, C and D.

When the probe is far away from the sample surface (the right part at point A on the curve), there is no interaction between the probe molecule and the asphalt molecule. As the probe is approaching the sample surface, the attractive force between the probe molecule and asphalt molecule makes the probe further move close to the sample (the AB part on the curve). This attractive force reaches its maximum value at point B beyond which the attractive force gradually turns into the repulsive force which stops the probe approaching. The closer the probe gets to the surface of sample, the faster the repulsive force grows (the BC part on the curve). The repulsive force reaches its peak at point C when the probe molecule gets infinitely close to the asphalt molecule. Then, the probe begins to get away from the sample surface. At the beginning, the attractive force dominates the interaction between the probe molecule and asphalt molecule, and this attractive force increases with the increase in the distance between these



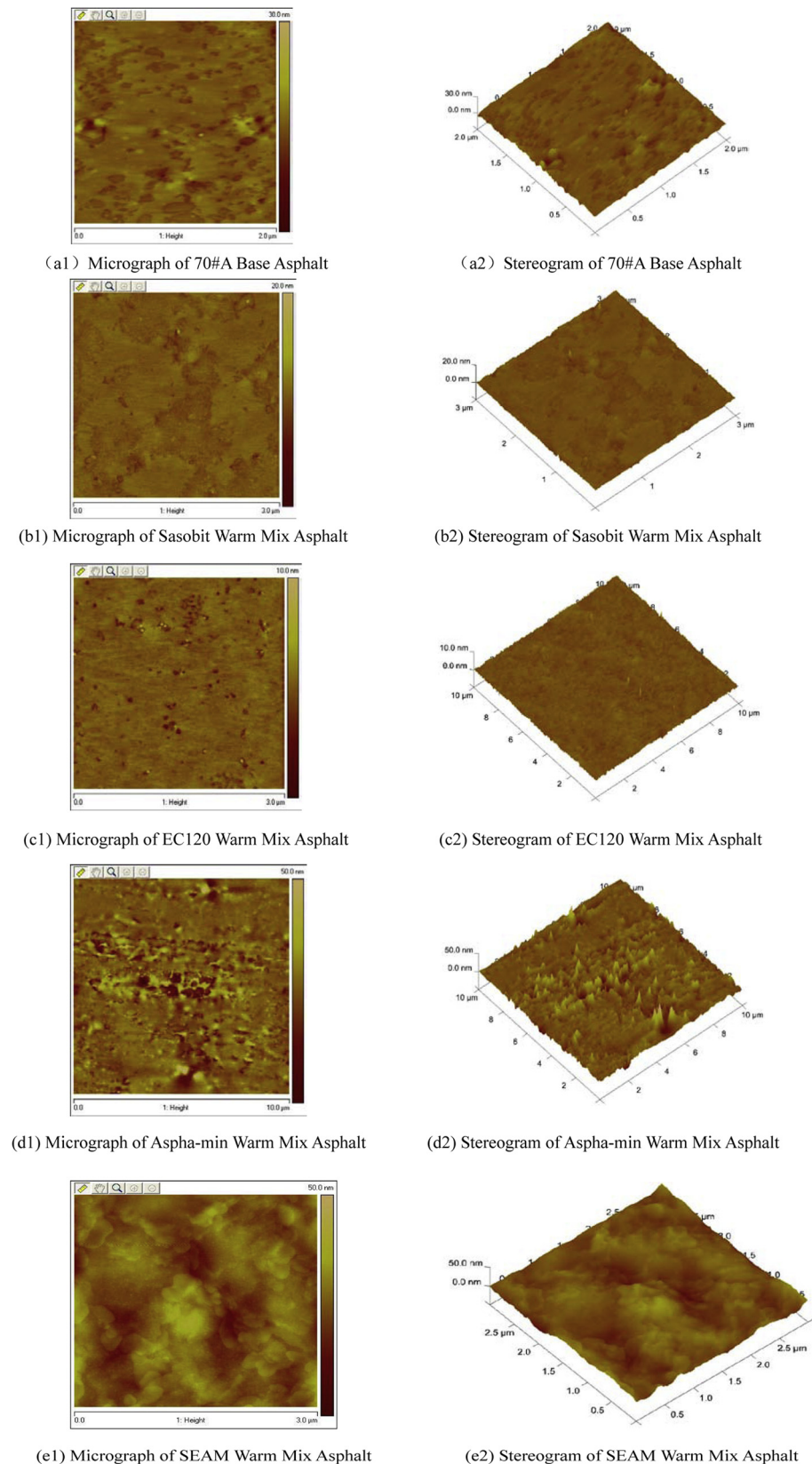


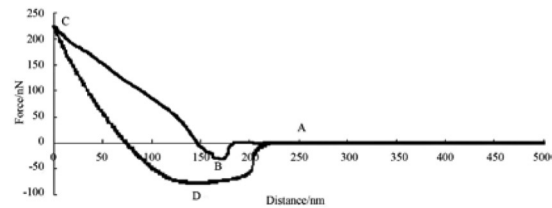
Fig. 3. Typical surface images of each asphalt binder (dry sample).

two molecules (the CD part on the curve), reaching the maximum value at point D. After point D, the probe molecule gets rid of the restriction of adhesion force from the

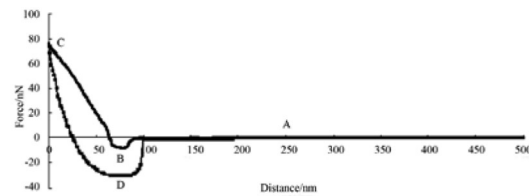
asphalt molecule and slowly returns to the initial state (the DA part on the curve). The corresponding value at point D represents the maximum adhesion force between

Table 2  
Roughness calculation results of each asphalt binder.

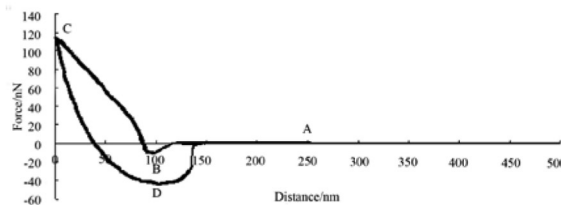
Type of asphalt		Dry			Wet		
		Average value (nm)	Maximum value (nm)	Root-mean-square (nm)	Average value (nm)	Maximum value (nm)	Root-mean-square (nm)
70#A base asphalt	Original	9.3	20.2	12.51	11.3	24.9	14.18
	After PAV aging	11.7	24.3	14.77	14.6	26.3	16.22
Sasobit warm mix asphalt	Original	9.9	19.8	13.13	12.5	24.6	14.27
	After PAV aging	12.1	17.6	15.32	14.5	26.9	17.73
EC120 warm mix asphalt	Original	6.5	9.6	7.71	8.3	14.2	8.85
	After PAV aging	8.9	12.1	9.54	11.2	18.3	12.16
Aspha-min warm mix asphalt	Original	21.2	41.7	24.11	24.3	46.2	28.56
	After PAV aging	23.7	45.9	27.86	28.9	48.8	31.12
SEAM warm mix asphalt	Original	24.1	44.6	28.35	27.3	49.4	30.52
	After PAV aging	28.3	48.5	29.97	30.1	48.9	32.46



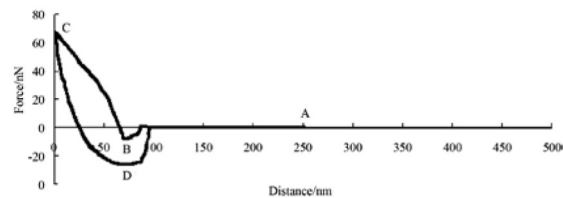
(a) 70#A Base Asphalt



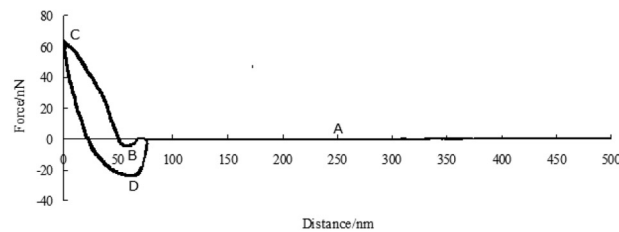
(b) Sasobit Warm Mix Asphalt



(c) EC120 Warm Mix Asphalt



(d) Aspha-min Warm Mix Asphalt



(e) SEAM Warm Mix Asphalt

Fig. 4. Force-distance test chart of each asphalt binder (dry sample).

the probe and asphalt molecules caused by the Van der Waals force [17,18].

## 6. The analysis of the tested results

### 6.1. The analysis of the tested results of original asphalt binders

The tested adhesion forces for original asphalt binders are given in Table 3.

Combined with the previous research, the process of water infiltration in asphalt binder is known as follows:

Hydrones have a tremendous polarity, and once water contacted with the asphalt surface, the interaction between hydrones and the polar molecules or groups such as aromatic hydrocarbons, colloids and asphaltenes in asphalt will take place by orientation forces, and a micro-activating center will then be formed by hydrones aggregation. Due to the directionlessness and saturability of orientation forces, the adsorbed hydrones will continue to interact with the polar groups nearby to form new micro-activating centers. Similarly, the micro-activating centers can also be formed through the induction forces between the hydrones and the nonpolar molecules & constituents,

Table 3  
Adhesion force test results of original asphalt binders.

Point	70#A base asphalt		Sasobit warm mix asphalt		EC120 warm mix asphalt		Aspha-min warm mix asphalt		SEAM warm mix asphalt	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1	103.7	71.3	49.6	38.5	71.3	67.5	117.4	125.4	98.7	84.6
2	88.9	52.5	52.7	42.7	67.9	69.4	113.1	119.6	117.4	88.2
3	111.2	47.9	58.8	46.8	68.5	55.6	102.8	132.7	105.9	95.7
4	101.5	50.7	59.1	44.3	77.4	57.9	98.6	121.5	93.5	99.6
5	86.5	58.5	54.3	39.6	73.5	63.1	97.9	118.3	102.6	80.3
6	88.2	47.8	55.6	37.2	70.1	67.3	95.4	119.0	95.5	83.1
7	107.4	46.7	56.1	45.8	69.0	56.6	103.8	125.7	93.9	101.5
8	85.3	63.4	52.5	47.5	66.4	55.8	96.9	116.4	112.6	87.6
9	91.2	67.9	58.4	40.9	72.2	68.3	109.3	121.0	96.2	92.5
10	114.1	57.3	56.9	48.7	70.8	61.5	119.8	117.5	103.6	83.9
Average (nN)	97.8	56.4	55.4	43.2	70.7	62.3	105.5	121.7	110.0	89.7
Standard deviation (nN)	10.415	8.346	2.959	3.824	2.996	5.279	8.425	4.693	11.108	6.923
Percent variation (%)	10.42	14.80	5.34	8.85	4.24	8.47	7.99	3.86	10.10	7.72

what's more, due to the directionlessness and saturability of the induction forces, just like the orientation forces, the hydrones will also continue to interact with the nonpolar constituents nearby. In addition, the hydrones will interact with the oxygen and nitrogen atoms in asphalt to form hydrogen bonds. Capillary channels for water enrichment and infiltrate constructed by micro-activating centers are formed by the above three types of intermolecular interactions, through these channels, water enriches in the asphalt layer and expand to the mineral aggregate surface. This is how the progress of water diffusion passage is formed. After it, hydrones continually get to reach the interface of the asphalt and mineral aggregates and interact with asphalt as mentioned above. More hydrones get into asphalt as the contact surface is getting large and then asphalt will get saturated and accommodates no hydrones any more when the interactions between hydrones and polar and nonpolar component & strong electronegativity elements were completed. In the progress, a slower capillary channel formation velocity means a smaller velocity of water diffusion, namely a greater capacity of water damage-proof and vice versa.

Based on the above analysis, conclusions from the AFM tests can be drawn: (1) the most gentle curve near point D comes from the original base asphalt in Fig. 4, which indicates that its viscosity is obviously greater than that of the warm mix asphalts. This is consistent with the previous studies. (2) For the original asphalt binders, the ranking order of the adhesion force under dry condition is: SEAM warm mix asphalt (110.0 nN) > aspha-min warm mix asphalt (105.5 nN) > 70#A base asphalt (97.8 nN) > EC120 warm mix asphalt (70.7 nN) > sasobit warm mix asphalt (55.4 nN). This means that under the dry condition the aspha-min warm mix asphalt and SEAM warm mix asphalt have better adhesion to the mineral aggregate than that of other asphalt binders. (3) Under the dry condition,

the standard deviation of the tested adhesion force for original base asphalt, aspha-min warm mix asphalt and SEAM warm mix asphalt are relatively large, showing a great dispersion degree of the tested results. (4) In comparison to the dry condition, the mean value of adhesion force in wet condition decreases by 47.2% for original base asphalt, by 22.0% for sasobit warm mix asphalt, by 11.9% for EC120 warm mix asphalt, by 13.3% for aspha-min warm mix asphalt and by 18.5% for SEAM warm mix asphalt. From the point of view of the absolute value, under the wet condition, the adhesion strength of aspha-min warm mix asphalt and SEAM warm mix asphalt is stronger than that of other warm mix asphalts, which shows a better resistance ability to water damage. According to the relative value, EC120 warm mix asphalt and aspha-min warm mix asphalt have the lowest moisture sensitivity. The adhesion force between the asphalt binder and the mineral aggregate is hardly impacted by the change of the moisture conditions outside, which leads to a better water-resistance ability.

The reasons are that: (1) the sasobit is a kind of long chain aliphatic hydrocarbon generated in the coal gasification process with the chain of carbon atoms ranging from C<sub>5</sub> to C<sub>100</sub>. It is essentially the paraffin fine crystals, mainly composed of –CH<sub>2</sub> and –CH<sub>3</sub>. As it is insoluble in water, the lubrication action of wax enhances the surface tension between the asphalt molecule and mineral aggregate under wet condition, which largely reduces the adhesion between asphalt and aggregate. (2) The EC120 is a kind of linear aliphatic hydrocarbon, with strong hydrophobicity and hydrophobic migration, which cannot dissolve in water due to many non-polar groups. The increase in the surface tension between the EC120 molecule and the mineral aggregate with the presence of water results in the decrease in adhesion force, but the influence is limited. (3) The aspha-min is a kind of artificial zeolite, very fine white pow-

der with meshy silicate composite structures among which there is space to accommodate the cations, molecules and ion group, like  $\text{Na}^+$ ,  $\text{Ca}^{2+}$  and  $\text{H}_2\text{O}$ . The aspha-min contains about 21% water. When the temperature is among  $85^\circ\text{C}$ – $182^\circ\text{C}$ , the released moisture induces the bubble effect in the asphalt, and the volume of asphalt binder increase, which makes the mix and compaction of asphalt mixture to be finished at relatively low temperature. On the other sides, due to the good adsorbability, good thermostability, openness and numerous cavities, when the electrically neutral molecules in asphalt are colliding or approaching the zeolite molecular particles, the Van der Waals' force inside the asphalt system turns into relatively big attractive force, dramatically enhancing the adhesion between the asphalt and the binder. (4) The SEMA is a kind of mixed additive composed of sulfur and auxiliaries, containing over 97% sulfur. Under the high-speed shearing of the colloid grinder, the very fine sulfur granules uniformly distribute inside the asphalt binders. Part of sulfur forms the meshy structure in the asphalt, which increases the high-temperature performance of the asphalt binder but decreases its viscosity, making the asphalt mixtures easily mix and stir, spread and compact, even at a low temperature. This part of sulfur mainly acts as diluent. The other part of sulfur uniformly distributes inside the asphalt binders in the form of crystal so that it can increase the strength and stability of the asphalt binders, but this part of sulfur does not dissolve in the water. Under the wet condition, the sulfur in the asphalt not only improves the surface tension but also absorbs the oil in the asphalt, which breaks the colloid balance structure of asphalt and reduces the adhesion force between the asphalt and mineral aggregate.

## 7. The analysis of the tested results of aging asphalt binders

The adhesion forces for aging asphalt binders are given in Table 4.

Table 4  
Adhesion force test results of aging asphalt binders.

Point	70#A base asphalt		Sasobit warm mix asphalt		EC120 warm mix asphalt		Aspha-min warm mix asphalt		SEAM Warm Mix Asphalt	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1	47.3	28.7	51.3	34.5	46.9	38.9	82.9	92.4	77.5	68.3
2	52.4	21.5	48.5	29.6	42.1	36.5	94.1	89.8	76.9	69.9
3	58.9	22.6	37.9	25.9	44.6	43.6	92.3	107.6	88.3	60.7
4	55.3	30.6	39.6	24.3	43.5	45.3	81.7	102.3	87.2	59.3
5	42.5	19.8	44.1	33.6	49.8	46.2	83.6	105.3	82.5	55.9
6	41.7	21.5	45.3	35.8	55.2	36.8	91.7	88.4	76.3	58.4
7	48.9	28.8	46.2	30.1	45.6	38.5	92.5	92.7	79.6	68.6
8	50.8	20.7	37.8	27.3	52.3	36.2	85.4	91.6	84.1	67.3
9	56.7	24.2	35.7	22.5	48.6	46.2	91.6	90.4	86.1	60.8
10	61.5	26.6	45.6	23.4	48.4	43.8	87.2	107.5	74.5	55.8
Average (nN)	51.6	24.5	43.2	28.7	47.7	41.2	88.3	96.8	81.3	62.5
Standard deviation (nN)	6.316	3.688	4.900	4.535	3.831	3.979	4.406	7.466	4.733	5.199
Percent variation (%)	12.24	15.05	11.34	15.80	8.03	9.66	4.99	7.71	5.82	8.31

The AFM test results show that: (1) compared with the original asphalt binders, the adhesion force of aging asphalt binders under dry condition decreases with different extents, in the order of 70#A base asphalt (47.2%) > EC120 warm mix asphalt (32.5%) > SEAM warm mix asphalt (26.1%) > sasobit warm mix asphalt (22.0%) > aspha-min warm mix asphalt (16.3%), which means that the aging process greatly lowers the moisture erosion resistance ability of all asphalt binders, further impairing the water damage resistance ability. The base asphalt is more sensitive to moisture and more vulnerable to water damage, no matter it is under original state or aging state. Among the five kinds of asphalt binders, the aging aspha-min warm mix asphalt, with the least loss of adhesion force and the relatively small dispersion degree of the tested adhesion force, has the maximum water-damage resistance ability. (2) The adhesion force between the aging asphalt binder and mineral aggregate also decreases under wet condition, following the order: 70#A base asphalt (56.6%) > EC120 warm mix asphalt (33.9%) > sasobit warm mix asphalt (33.6%) > SEAM warm mix asphalt (30.3%) > aspha-min warm mix asphalt (20.5%). This suggests that the water damage resistance ability remarkably decreases after aging and the aspha-min warm mix asphalt has the smallest decline.

## 8. Conclusions

- (1) The AFM can be used to measure the surface characteristic of warm mix asphalt binders and the adhesion force between the asphalt and the mineral aggregate. The method of the preparation of samples and the test method adopted in this work are valid and feasible.
- (2) For the original and dry samples, the adhesion force ranks in the order of SEAM warm mix asphalt > aspha-min warm mix asphalt > 70#A base asphalt > EC120 warm mix asphalt > sasobit warm mix



asphalt. Aspha-min warm mix asphalt and SEAM warm mix asphalt show better adhesive ability with the mineral aggregate in comparison to other asphalt binders, but their test results have relatively large dispersion and fluctuation.

- (3) With respect to the original and wet samples, aspha-min warm mix asphalt and SEAM warm mix asphalt show stronger water damage resistance ability; EC120 warm mix asphalt and aspha-min warm mix asphalt are less sensitive to moist and have stronger ability to resist water erosion, since the external moisture condition change has very small influence on the adhesion force.
- (4) The aging process significantly reduces the moisture erosion resistance ability, which further impairs the water damage resistance ability under the rank of 70#A base asphalt > EC120 warm mix asphalt > SEAM warm mix asphalt > sasobit warm mix asphalt > aspha-min warm mix asphalt.
- (5) The base asphalt is more sensitive to moisture and more vulnerable to water damage, no matter whether it is under the original or aging state.
- (6) No matter it is dry or wet, the aging aspha-min warm mix asphalt has the least loss of adhesion force, the smallest dispersion of the tested adhesion force, the strongest water-damage resistance ability.

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